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Advanced Compact Holographic Data Storage System

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Abstract— JPL, under current sponsorships from NASA Space Science and Earth Science Programs, is developing a high-density, nonvolatile and rad-hard Advanced Holographic Memory (AHM) system to enable large-capacity, high-speed, low power consumption, and read/write of data in a space environment. The entire read/write operation will be controlled with electro-optic mechanism without any moving parts. This CHDS will consist of laser diodes, photorefractive crystal, spatial light modulator, photodetector array, and I/O electronic interface. In operation, pages of information would be recorded and retrieved with random access and high-speed. The nonvolatile, rad-hard characteristics of the holographic memory will provide a revolutionary memory technology to enhance mission capabilities for all NASA's Earth Science Mission.

In this paper, recent technology progress in developing this CHDS at JPL will be presented. The recent applications of the CHDS to optical pattern recognition systems as a high density, high transfer rate memory bank will also be discussed.

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1. INTRODUCTION

NASA's future missions would require massive high-speed onboard data storage capability to support both Earth Science and Space Science missions. With regard to Earth science observation, a 1999 joint Jet Propulsion Laboratory and Goddard Space Flight Center (GFSC) study ("The High Data Rate Instrument Study" [1]) has pointed out that the onboard science data (collected by high date rate instruments such as hyperspectral and synthetic aperture radar) stored between downlinks would be up to 40 terabits (Tb) by 2003. However, onboard storage capability in 2003 is estimated at only 4 Tb that is only 10% of the requirement. By 2006, the storage capability would fall further behind to be able to only support 1% of the onboard storage requirements.

For Space Science, the onboard data storage requirements would be focused on maximizing the spacecraft's ability to survive fault conditions (i.e. no loss in stored science data when spacecraft enters the "safe mode") and autonomously recover from them NASA's long-life and deep space missions. This would require the development of non-volatile memory. In order to survive in the stringent environment during space exploration missions, onboard memory requirements would also include: survive a high radiation environment (1 Mrad), operate effectively and efficiently for a very long time (10 years), and sustain at least a billion (10^{12}) write cycles.

Therefore, memory technologies requirements of NASA's Earth Science and Space Science missions are: large capacity, non-volatility, high-transfer rate, high radiation resistance, high storage density, and high power efficiency.

Current technology, as driven by the personal computer and commercial electronics market, is focusing on the development of various incarnations of Static Random Access Memory (SRAM), Dynamic Random Access Memory (DRAM), and Flash memories. Both DRAM and SRAM are volatile. Their densities are approaching 256 Mbits per die. Advanced 3-D multichip module (MCM) packaging technology has been used to develop solid-state recorder (SSR) with storage capacity of up to 100 Gbs [3]. The Flash memory, being non-volatile, is rapidly

Table I. A comparative chart for memory specifications

Feature	SRAM	DRAM	Flash	Holographic
Non-volatile	No	No	Yes	yes
Organization (bits/die)	512k x8 (rad hard)	16Mx8	16Mx8, 32Mx8	10 Gb/cm^3
Data Retention (@70^0 C	N/A	N/A	> 10 yrs	> 10 yrs
Endurance (Erase/write Cycles)	unlimited	unlimited	10^6 (commercial)	unlimited
Access Time, t (acc)	< 10 ns	< 25 ns	50 ns	1 ms/page
Data Transfer rate	> 800 Mb/sec	> 320 Mb/sec	160 Mb/sec	> 1 Gb/sec
Radiation (Total Dose)	1 Mrad	< 50 kRads	< 30 kRads	> 1 Mrad
Power	1 Gb/watt	1 Gb/watt	10 Gb/watt	10 Gb/watt
Package	4 Mb (die stacking) 100's Gb (Multichip Module)	128 Mb (per die) 100's Gb (MCM)	128 Mb & 256 Mb (per die) 100's Gb (MCM)	10 Gb/cm^3 cube. 1 Tb/card

gaining popularity. Densities of flash memory of 256 Mbits per die exist today. High density SSR could also be developed using the 3-D MCM technology. However, Flash memory is presently faced with two insurmountable limitations: Limited endurance (breakdown after repeated read/write cycles) and poor radiation-resistance (due to simplification in power circuitry for ultra-high density package).

It is obvious that state-of-the-art electronic memory could not satisfy all NASA mission needs. It is necessary to develop new memory technology that would simultaneously satisfies non-volatility, rad hard, long endurance as well as high transfer rate, low power, mass and volume has yet been developed to meet all NASA mission needs.

The comparative specifications of the holographic memory (design goal) and state-of-the-art electronic memory are listed in Table I. As shown in Table I, the holographic memory technology, upon full development, not only is simultaneously non-volatile, high-speed and rad hard, but also superior in power and volume/mass efficiency than its electronic counterpart.

2. HOLOGRAPHIC DATA STORAGE TECHNOLOGY

The Advanced Holographic Memory (AHM) system will store data in large number of holograms inside of a photorefractive crystal. Holograms are formed by recording the light interference pattern between a page of optical modulated data (image or binary bits) and a reference laser beam in a cubic photorefractive crystal. Since these images are stored in the Fourier domain and recorded in three dimensions, massive redundancy are built into the holograms such that the stored holograms would not suffer from imperfections in the media or point defects. The $LiNbO_3$ photorefractive crystal has been the most mature recording material for holographic memory due to its uniformity, high E-O coefficient, high photon sensitivity, and commercial availability. One unique advantage for using holographic data storage is its rad hard capability. Holograms stored in photorefractive crystal have been experimentally proven to be radiation-resistant. In a recent NASA LDEF (Long-Duration Exposure on Active Optical Components) experiment, Georgia Institute of Technology (GIT), under NASA Contract NAS1-15370, has flown a Lithium Niobate holographic memory in space. The retrieved crystals only suffered surface damage and still retained their photosensitivity for hologram recordings.

With regarding to the lifetime of stored data in the $LiNbO_3$ material: without a thermal fixing process after recording, data stored $LiNbO_3$ material would only have up to 1 month of shelf life. With thermal fixing, the stored will stay unchanged for many years. Recently, a technology breakthrough in extending storage lifetime of photorefractive memory from months to decades or longer have been achieved by researchers at Caltech and other institutions [4-5]. A new two-photon recording material, doubly doped Fe:Mn: LiNbO3, has been developed. This material possesses a deep traps partially filled with electronics and a shallow (intermediate) traps to trap photo-generated electrons with very long lifetime. Doubly doped extrinsic dopants (Fe^{+2}, Mn^{+2}) would provide this intermediate state. As illustrated in Figure1:

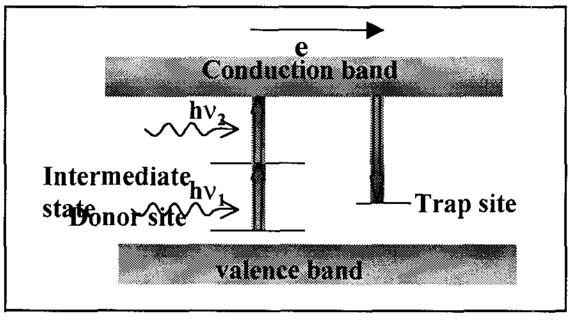


Figure 1a. Nonvolatile hologram recording

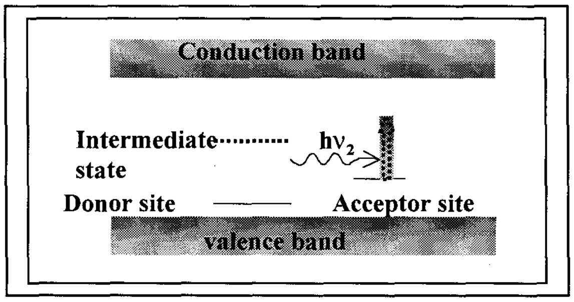


Figure 1b. Nonvolatile hologram readout

During recording, a first photon (from a ultraviolet light source) is used to excite an electron form the Valence band to an intermediate state. A hologram writing photon is then used to bring the electron up to the Conduction band. The electron will then migrate and get trapped to record the interference pattern. During readout, the readout beam will readout the hologram but is with insufficient energy to elevate the electron to the conduction band. Hence the stored hologram will not be erased during readout.

Recently, we developed a bench-top AHM Data Storage breadboard and, for the first time, demonstrated video-rate of memory retrieval for both grayscale image and binary data. A 1000-page long video of Asteroid Toutatis images were recorded and retrieved with very high fidelity. The AHM breadboard used acousto-optic (AO) scanning for multiple holograms recording and readout without any moving parts. This initial development has demonstrated the high fidelity, high-speed data storage capability. A photo of the AO based AHM system and its schematic diagram is shown in Figure 2.

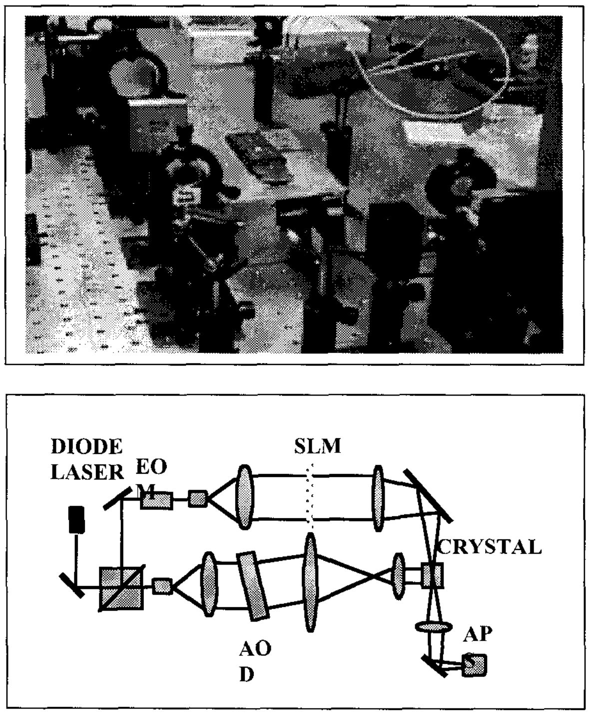


Figure 2. Photograph of the JPL developed AO- based AHM system and its corresponding schematic diagram

An experimental demonstration of the grayscale image recording and retrieving capability has been achieved. Sample of high-fidelity retrieved image set of NASA's image data of asteroid Toutatis is shown in Figure 3.

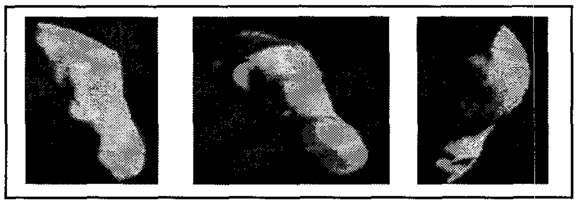


Figure 3. Grayscale Toutatis images retrieved from JPL developed holographic memory

This JPL-developed proof-of-concept acousto-optic-scanner-based holographic memory system has demonstrated the super performance of holographic memory. This breadboard is currently being used for bit error rate analysis of the retrieved holographic data.

In order to miniaturize the AHM breadboard, the AO beam steering devices will be replaced by a liquid crystal beam steering spatial light modulator (BSSLM). This device will provide high-resolution beam steering capability to enable the storage /retrieval of more than 10,000 pages of holographic memory. By coupling the BSSLM with a VCSEL array, the storage density will further be increased by more than two orders of magnitude. The introduction of the BSSLM spatial multiplexing scheme would further ensure the system is compact and low power.

3. ADVANCED HOLOGRAPHIC MEMORY USING LIQUID CRYSTAL BEAM STEERING DEVICES

The proposed holographic memory architecture, as shown in Figure4, consists of a writing module for multiple holograms recording and a readout module for hologram readout. The writing module include a laser diode as the coherent light source, a pair of cascaded beam steering Spatial Light Modulators (BSSLM), one transmissive and one reflective in each pair, for angular multiplexed beam steering, a Data SLM for data input for storage, two cubic beam splitter for beam forming, and a photorefractive crystal for hologram recording. The readout module also shares this photorefractive crystal. The readout module includes a laser diode with the same wavelength as the writing one, a pair of cascaded BSSLMs to generate phase conjugated readout beam (i.e. the readout beam is directed in opposite of that of the writing beam), the shared photorefractive crystal, a cubic beam splitter, and a photodetector array for recording the readout holograms The system uses angle multiplexing scheme to store multiple holograms and phase-conjugated beams to readout each holograms.

In hologram writing, the collimated laser beam (top left in Fig.4) splits into two parts at the first cubic beam splitter. 1) The horizontally deflected light will travel across the second cubic beam splitter to read out the input data after impinging upon the Data SLM. The data-carrying beam will then be reflected into the PR crystal as the data-writing beam. 2) The remaining part of the laser beam will go through vertically, passing a BSSLM and then reflected to the second reflective BSSLM. Both BSSLMs are 1-D blazed phase gratings capable of beam steering with an angular deflection determined by the grating periods. By cascading two BSSLMs in orthogonal, 2-D beam steering can be achieved (in the future, only a single 2-D beam steering SLM will be needed). This deflected laser beam will then be directed toward the PR crystal as the reference-writing beam. It will meet the data carrying writing beam inside the PR crystal to form an interfering grating (hologram). Each individual hologram is written with a unique reference angle and can only be readout at this angle (or its conjugated one). By varying the reference beam angle in sequential recording, very large number of holograms can be recorded in the recording medium.

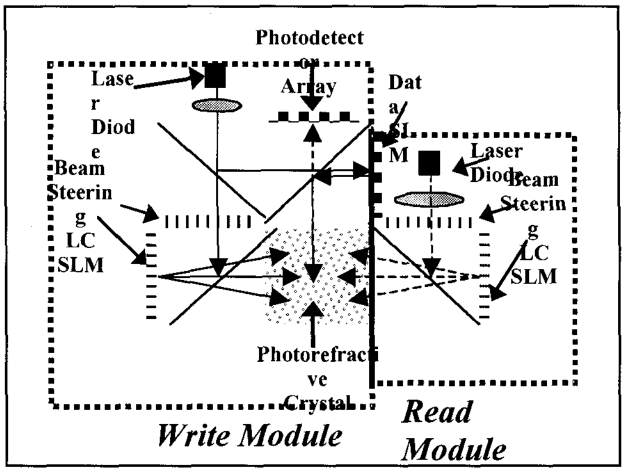
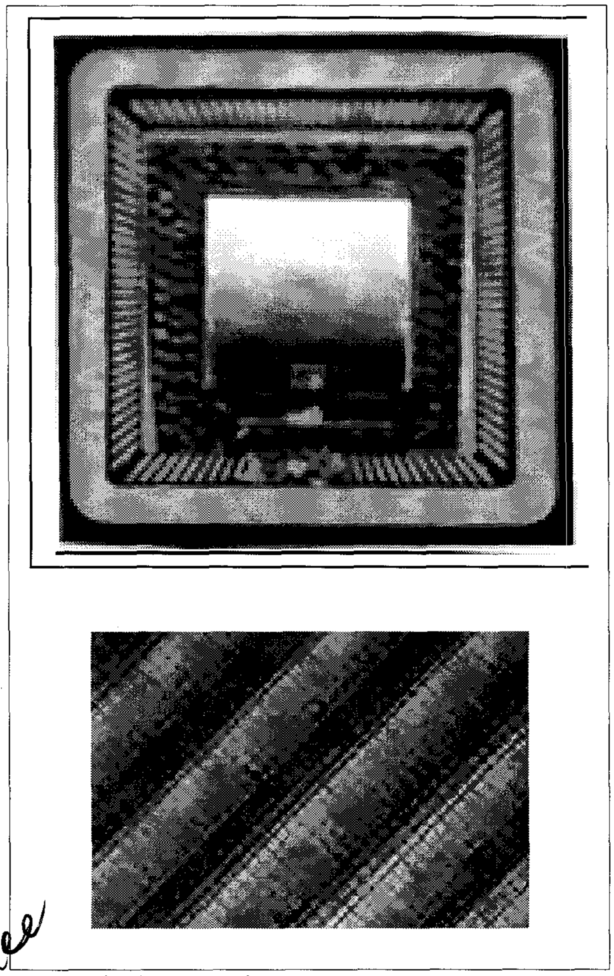


Figure 4. System schematic architecture of an Advanced Holographic Memory

For hologram readout, we have devised innovative phase conjugation architecture. This phase conjugation scheme will enable lensless hologram readout with minimal distortion (low bit error rate). As shown in Fig.4, a second pair of transmissive and reflective BSSLMs combination will be used to provide a phase-conjugated readout beam (with respect to the writing reference beam). After the beam impinges upon the PR crystal, the diffracted beam from the recorded hologram will exit the PR crystal backtracking the input data beam path, due to phase-conjugation property. It then directly impinges upon the photodetector array without the need of focusing optics and reconstruct the corresponding data page, as was recorded and stored in the PR crystal.

4. BEAM STEERING SPATIAL LIGHT MODULATOR

JPL has recently collaborated with the Boulder Nonlinear System Co. (BNS) to develop a BSSLMS. This device is built upon a VLSI back plane in ceramic PGA carrier. A 1-dimensional array of 4096 pixels, filled with Nematic Twist Liquid Crystal (NTLC), is developed on the SLM surface. The device aperture is of the size of 7.4 mm x 7.4 mm, each pixel is of 1 mm x 7.4 mm in dimension. Currently, the response time can reach 200 frames/sec. In future, by replacing the NTLC with Ferroelectric Liquid Crystal (FLC), the speed may be increased by at one order of magnitude (i.e. > 2000 frames/sec). A photo of this



BSSLM is shown in Figure 5.

Figure 5 a photographic of a 1 x 4094 Beam Steering Spatial Light Modulator and a magnified view of the grating structure of the SLM.

The principle of operation of this BSSLM is illustrated in Figure 6. Since the SLM is a phase-modulation device, by applying proper addressing signals, the optical phase profile (i.e. a quantized multiple-level phase grating) would repeats over a 0-to-2p) ramp with a period d. The deflection angle q of the reflected beam will be inversely proportional to d:

$$\theta = \sin^{-1}(\lambda/d)$$

Where λ is the wavelength of the laser beam. Thus, beam steering can be achieved by varying the period of the phase grating

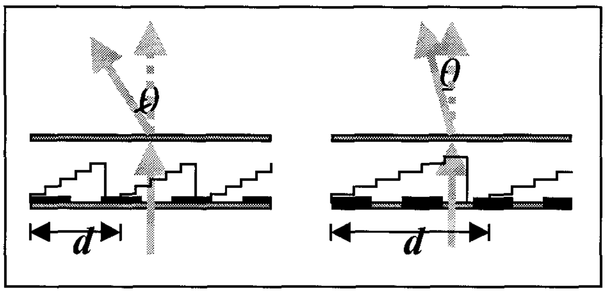


Figure 6. Beam steering using a phase modulation SLM with variable grating period.

The diffraction efficiency, η, of this device is

$$\eta = \left(\frac{\sin(\pi/n)}{\pi/n}\right)^2$$

Where n: number of steps in the phase profile. For example η ~ 81% for n =4, and η~95% for n =8.

Number of resolvable angles can be defined by:

$$M = 2m/n + 1$$

Where m is the pixel number in a subarray, and n is the minimum number of phase steps used. For example, M = 129 for m=512, n =8 with a 1 x 4096 beam steering device.

Primary advantages of using such a electro-optic beam steering device for angular multiplexing for holographic data storage include: No mechanical moving parts; Randomly accessible beam steering; Low voltage / power consumption; Large aperture operation; No need for bulky frequency-compensation optics as in AO based devices.

It has been demonstrated at Caltech that up to 160,000 pages (i.e. 160 Gb of memory) of hologram were stored in a $LiNbO_3$ PR crystal with 1 cm^3 volume using a scanning mirror to create angular multiplexing for each reference beam. However, the scanning mirror scheme that requires mechanically controlled moving parts is not suitable for space flight. In this proposal, we would like to develop an all electro-optic controlled angular multiplexing scheme with high-speed and high resolution. We have solved this problem by utilizing an all-phase beam steering device, the BSSLM.

Both transmissive and reflective BSSLMs are planned to use in the AHM system under development at JPL. The current transimissive BSSLM device is a 1 x 1024 array with resolvable spots about 64. The reflective BSSLM device is a silicon-based 1-D diffractive beam steering device. The current device is a 1 x 4096 array, which has about 128 resolvable spots. Devices of higher number of resolvable spots (around 180) will soon be available. Thus total resolvable spots from these cascaded BSSLMs would be around 11,520. By using two cascaded BSSLMs for beam steering, a total of more than 10,000 pages of hologram can be stored and readout in a single cubic centimeter of PR crystal. Since each page can store about 1000 x 1000 pixels of data (1 Mbytes), the total storage capacity will reach 10 Gigabytes.

5. CONCLUSIONS

The proposed holographic memory possesses the unique advantages over all state-of-the-art holographic memory systems. These advantages are: high storage capacity (10 Gigabytes per module), high-speed (1ms per page), and low-power (100mW laser power for writing, 10mW for readout).

Use laser diode as writing source (the state-of-the-art laser diode can provide power of 100mW). This will enable us for a miniature packaging of the whole system.

- Use angular multiplexing with a pair of BSSLMs. This will enable the recording of up to 10,000 pages of hologram in a 1 cubic centimeter PR crystal without moving parts.
- Use phase-conjugation readout scheme enables us to achieve high fidelity retrieval and compact system architecture.

6. ACKNOWLEDGEMENT

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